

Well-to-wheel life cycle assessment of *Eruca Sativa*-based biorefinery



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ABSTRACT

Renewable energy generation through biorefineries is increasingly considered as more sustainable in comparison with fossil-based fuels as well as single-product renewable energy systems. However, biorefineries have many system variations, and therefore, the evaluation of their environmental performance and comparison with conventional systems before large-scale deployment is essential. In this paper, the sustainability of three different biorefinery scenarios (Sc-1, Sc-2, and Sc-3) based on *Eruca sativa* (ES) as feedstock were investigated using a life cycle assessment approach from energy balance and environmental point of views. Biodiesel, electricity, ethanol, heat, glycerol, and/or biomethane were the marketable products taken into account under the conditions of these scenarios. According to the results obtained, we argue that although biorefineries offer unique features as most effective alternatives for mitigating climate change and reducing dependence on fossil fuels, the selection of biomass processing options and management decisions can widely affect the final evaluation results. Overall, providing transportation fuel through Sc-2 in which biodiesel, electricity, ethanol, heat, and glycerol were produced could decrease GHG emissions by approximately 140% compared with the combustion of neat diesel while also offering a total net energy gain (NEG) of 4.94E+08 MJ/yr. Nevertheless, if biorefineries are to be used for future transportation fuel production, a great deal of efforts should still be made to achieve better environmental performance in the Human Health and Ecosystem quality damage categories.

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1. Introduction

Rapid depletion of fossil resources and the intensifying environmental problems caused by the intensive use of these energy carriers seem to serve as strong drive to further increase the share of renewable energy carriers on the market [1,2]. On the other

hand, while less concern is raised about the future supply of renewable electricity and heat due to the availability of a variety of renewable alternatives (i.e., wind, solar, hydro, biomass, and others), major concerns still exist regarding the transportation sector and the role renewable energies could play to transform this sector remarkably. This is specifically true about the next few decades when the sector has been anticipated to highly rely on biomass-derived energy carriers, also known as biofuels [3].

Historically, initial attempts led to the production of first generation biofuels mainly produced from various feedstocks such as soybean [4–6], corn [7–9], and rapeseed [10–12]. However, in spite of technological availability and economic viability, they suffer from serious drawbacks including food vs. fuel competition over water/

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Abbreviations

NH ₃	Ammonia
ES	<i>Eruca sativa</i>
FER	Fossil Energy Ratio
FU	Functional unit
GHG	Greenhouse gas
LUC	Land use change
LCA	Life cycle assessment
LCI	Life cycle inventory
NEG	Net Energy Gain
NO ₂	Nitrogen dioxide
NO _x	Nitrogen oxides
N ₂ O	Nitrous oxide
SSF	Simultaneous saccharification and fermentation

land, land use change (LUC), biodiversity loss, and feedstock limitation [13–16]. Hence, second generation biofuels mainly produced from a variety of biomass resources including non-food crops and residues were introduced and evaluated. In spite of their many advantages, the expensive and sophisticated technologies used for producing these biofuels have imposed serious limitations on their profitability and economic viability [17].

To overcome the changes faced to enhance the economic viability features of the second generation biofuel as future transportation fuel, the biorefinery concept has been frequently investigated [18–20]. In fact, the main objective of a biorefinery as presented by the International Energy Agency Bioenergy Task 42, is to produce a spectrum of marketable products in order to maximize the profitability of a given system [3,21]. As for biofuels, the biorefinery concept is translated by integrating different biomass conversion processes in order to produce multiple products of high economic value, e.g., bioethanol, methane, and heat from sugarcane bagasse [21]. It should be mentioned that although economic aspects are of critical importance in achieving a viable energy system, they only constitute one vertex of the sustainability triangle. This means that environmental and energy analyses should also be taken into account to correctly define the behavior of a given bio-fuel system under consideration [22].

Life Cycle Assessment (LCA), a method by which the potential environmental impacts of a product system could be evaluated through its life cycle [23], is a valuable approach to point out the environmental aspects of biofuel biorefineries and to compare these renewable systems with petroleum refineries. This could assist with finding a trade-off among different energy generation scenarios leading to the employment of the more economic and sustainable ones [24]. In fact, this approach has been widely used to build the eco-profile of various biofuels such as bioethanol [25–28], biogas [14,29,30], and biodiesel [31–34]. The use of LCA methodology for investigating the biorefinery concept for sustainable production of biofuels and biomaterials has proved to be promising and has been attracted a great deal of interest [3,35–37].

Plants producing non-edible oils have been introduced as appropriate feedstocks for developing future biorefineries because they can address the controversies caused by using edible oils as energy feedstocks, i.e., high cost and food security conflicts [19,38]. Moreover, they can be grown on degraded agricultural soils, infertile wastelands as well as marginal and low grade lands while leading to increased soil carbon pool due to LUC [18]. However, in large scale energy production systems, they may require fertile soil and good farm practices in order to produce economically-viable

yields which could consequently result in higher environmental burdens [39]. On the other hand, the process options by which a given feedstock is treated in a biorefinery could also widely affect the amount of energy produced, and consequently the environmental burdens released to the ecosphere.

Among different non-edible oils used so far for second generation biofuel production, *Eruca Sativa* (ES) has recently attracted a great deal of attention as a valuable biofuel feedstock within the biorefinery framework [39–42]. This is ascribed to the unique characteristics of this plant, i.e., excellent resistance to drought, poor soil conditions, and diseases, as well as its potential to be used for multiple biofuels production [19,38]. ES could be cultivated on weak and dry lands while waste water could be used for irrigation [38,42]. To the best of our knowledge, only one study exists in which biodiesel production from ES with a biorefinery approach was taken into account and the other reports available were only focused on biodiesel production from ES seeds [19], ignoring the high potential of ES leaves, stems, and seed cake, remaining after oil extraction, for biomethane and ethanol production. Moreover, the biorefinery-based study conducted previously with focus on ES as the feedstock failed to include the environmental considerations in the analyses. Moreover, it did not consider the different process management options by which ES feedstocks could be treated in a biorefinery, while these process management strategies could have deeply influenced the system's economy and pollution issues.

Therefore, the present study was set to investigate three distinctive scenarios for production of ES biodiesel and relevant co-products based on a biorefinery approach while a thorough LCA was also carried out taking into account ES cultivation, harvesting, transport, processing, conversion, as well as the final use of the produced ES biodiesel in diesel engines. To show the potential benefits and/or drawbacks of ES biodiesel production on a biorefinery scale, the results were also compared with a fossil fuel reference, i.e., mineral diesel, when ES biodiesel used to replace fossil fuels.

2. Materials and methods

2.1. Goal and scope of the study

This study was conducted based on the ISO 14040 guidelines [23,43]. The goal of the present study was to use LCA to comparatively investigate the environmental consequences of different scenarios set forth for ES biodiesel production with a biorefinery approach as well as its consumption in diesel engines. ES plant, an annual or biannual herb which is an important non-edible oil crop in the drought and half-drought regions [19,38], was selected as the feedstock for the developed biorefineries. As mentioned earlier, ES plant (seeds and residuals) was chosen as the feedstock owing to its favorable characteristics such as excellent resistance to drought, poor soil conditions, and diseases along with its potential to be used for multiple biofuels production such as biodiesel, bioethanol, and biomethane [19,39,44].

In order to accomplish the goal of the present study, three distinctive biorefineries were defined on the basis of specific types of feedstock processing options, resulting in producing different types and amounts of biofuels and bioenergies. In another word, different feedstock processing alternatives were evaluated to identify the most sustainable and environmentally-friendly biorefinery scenario. Iran was considered as the location of the plants but the findings will be of interest worldwide. Moreover, in order to draw general conclusions about the results obtained herein, a fossil reference system, i.e., neat diesel fuel delivering the same amount of energy through its combustion was also taken into account. This comparison would help to show the potential benefits/drawbacks

of ES-based biorefineries when employed to replace fossil fuels. Energy policy makers, domestic and foreign investors interested in investing in renewable energy systems, and those concerned about energy and environmental issues were regarded as the audience of the present study.

It should be highlighted that what makes this study different from those conducted on ES biodiesel production is the implementation of a biorefinery approach. The main advantage of a biorefinery is the possibility to convert almost all fractions of a given feedstock into different value-added products which could enhance the overall economic viability of the process while reducing wastes disposal. A large number of studies have focused on biodiesel production from ES seeds [38,39,41,42], while the residual biomass such as ES leaves, stems, and seed cake, remaining after oil extraction, was not considered. These residual parts could have had a high potential for biomethane and ethanol production [19]. Moreover, although the application of ES oil as feedstock for biochemical production has been investigated [40] but the above-mentioned studies failed to take this aspect into account as well. On the other hand, few research works in which a biorefinery approach was considered, did not include environmental considerations in their analysis [19]. The other feature differentiating the present study from the previous reports on ES plant was the fact that the present study profoundly looked into the different process management options by which ES feedstocks could be treated through a biorefinery framework. This study also strived to find appropriate future transportation fuels while investigating their limitations in terms of production and consumption. Overall, this was, to the best of our knowledge, the first attempt to develop a biorefinery in order to meet both biofuel and biochemical requirements using ES feedstock.

The considered system boundary for this study is presented in Fig. 1. The selected system boundary included raw materials, ES

cultivation, feedstock transportation, production and use of energy carriers, as well as combustion stage in a diesel engine. ES cultivation stage included the application of agricultural inputs as well as farm operations resulting in on-site emissions. ES seeds and residuals were then transported to the biorefinery for further processing and a spectrum of different marketable co-products along with their consequent emissions were produced. Based on the scenario taken into consideration, electricity, biodiesel, ethanol, heat, glycerol, and/or biomethane were the marketable co-products of the biorefineries. Moreover, as can be observed in Fig. 1, the system boundary was also expanded to include the combustion of B100 and its consequent engine emissions.

In order to be able to compare the three developed scenarios with each other and the reference system (i.e., diesel), 1 GJ output energy obtained through the combustion of ES biodiesel was considered as functional unit (FU).

2.2. Life cycle inventory (LCI)

Due to the fact that this study included three distinctive stages, i.e., cultivation, biorefinery, and combustion, LCI of each stage will be discussed separately.

2.2.1. ES cultivation

ES is a species of the family Brassica which encompasses a large number of species including oilseed rape (canola) [19,45]. As mentioned earlier, this plant can well tolerate drought and poor soil conditions, and therefore, it can be cultivated in marginal and set-aside lands. For the purpose of providing feedstock for the developed biorefineries and in order to avoid competition with food crops over water and land, it was assumed that only marginal and set-aside land would be dedicated to ES cultivation. It is worth noting that cultivation in these types of lands can result in low

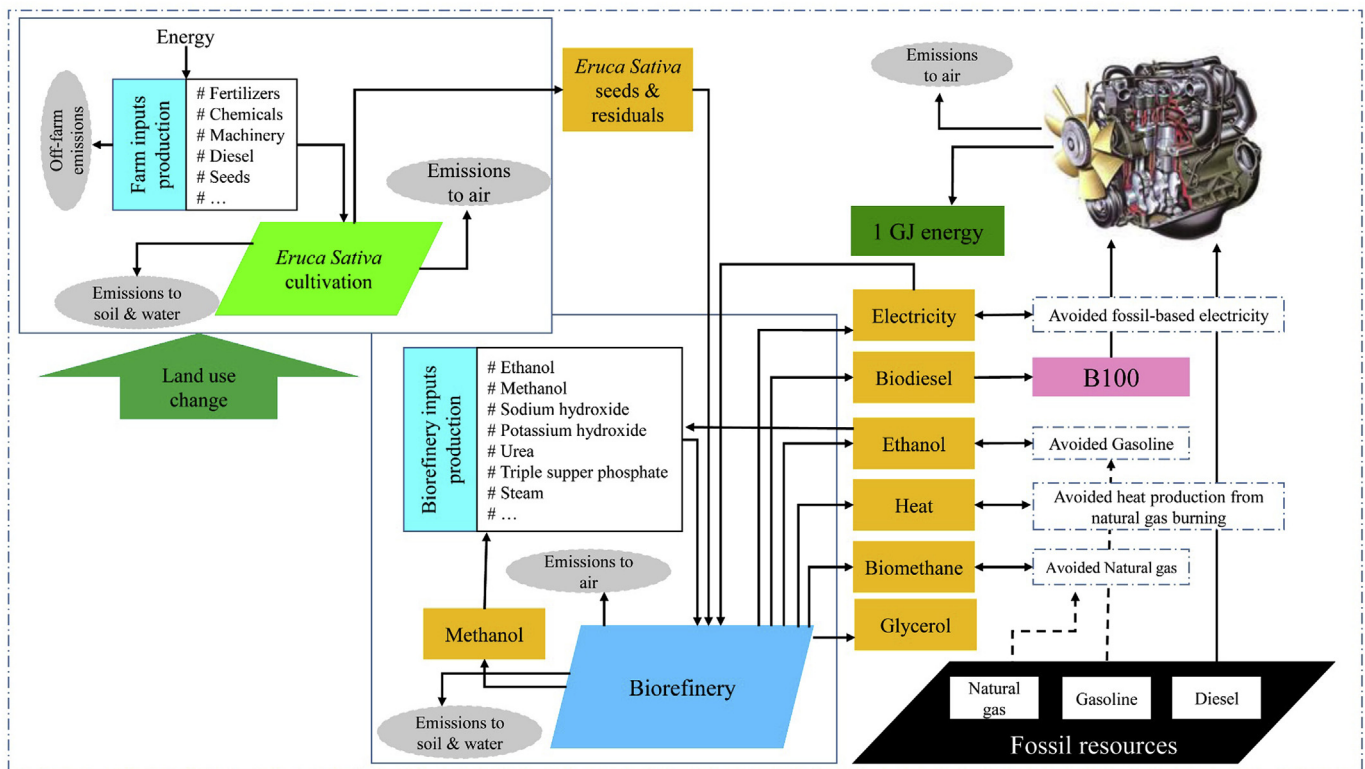


Fig. 1. System boundary: all the methanol produced by the biorefineries was internally used, only a fraction of the electricity and ethanol generated was internally consumed.

yields due to poor soil conditions while for a large scale plantation with the aim of supplying adequate amounts of feedstock for a large scale biorefinery, good farm operation practices and fertilization would be inevitable [46]. Accordingly, in order to avoid any under/over estimation of crop yields and nutrient requirements, farm inventory data were borrowed from the literature by carrying out a comprehensive literature review [45,47–51]. The inventory data about the agricultural inputs, energy carriers, and farm machineries are presented in Table 1.

Moreover, the application of chemical fertilizers and energy carriers in farm operations could cause on-site emissions, i.e., emissions to soil, water, and air. Therefore, the following emissions were also taken into consideration for the cultivation phase:

1. NH_3 emission due to the application of chemical fertilizers
2. CO_2 emissions as a result of urea application
3. Direct and indirect N_2O emissions
4. Nitrogen oxides emissions
5. Nitrate leaching
6. Phosphorus leaching
7. Heavy metal emissions to soil and water
8. Emissions corresponding to diesel fuel combustion during farm operations

Application of N-based fertilizers could cause ammonia (NH_3) emissions and was considered in LCI of ES cultivation. As described by IPCC, a country's specific data would be the best option for estimating aforementioned emissions. But in the case where specific data are not available, the emissions could be estimated using developed models. Accordingly, several methods have been developed for NH_3 emission assessment such as EMEP/EAA guidelines from the European Environment Agency and Agramon. Nemecek et al. [52] developed a model based on the EMEP guidelines 2013 for NH_3 emissions through the application of mineral fertilizers as follows:

$$\text{NH}_3 = (17/14) \times \sum_{m=1}^M (\text{EFa}_m \times p \times N_{\min} + \text{EFb}_m \times (1 - p) \times N_{\min}) \quad (1)$$

where NH_3 represents the amount of NH_3 emissions (kg NH_3) due to application of mineral fertilizers; EFa and EFb are emission

factors (kg $\text{NH}_3\text{-N/kg N}$) for soil with $\text{pH} = 7$ and $\text{pH} > 7$, respectively. “m” stands for the type of mineral fertilizer while “p” denotes the fraction of soils with $\text{pH} = 7$ and “min” refers to mineral N supplied by fertilizers [52].

Nitrification process of N-based fertilizers can result in NO_x emissions. The default emission factor of 0.026 kg/kg N-fertilizer applied, suggested by EMEP [53], was used to calculate NO emissions which was then multiplied by (46/30) to be converted to NO_2 [52].

Another emission which needed to be dealt with was Nitrous oxide (N_2O), a very powerful greenhouse gas. Estimation of direct N_2O emission was performed following the guidelines proposed by Nemecek et al. [52] in which the total nitrogen in mineral and organic fertilizers (N_{tot}), nitrogen contained in the crop residues (N_{cr}), NH_3 emissions, Nitrogen dioxide emissions (NO_2), and nitrate leaching (NO_3) were incorporated into the following equation:

$$\text{N}_2\text{O} = (44/28) \times (0.01 \times (N_{\text{tot}} + N_{\text{cr}} + (14/17) \times \text{NH}_3 + (14/46) \times \text{NO}_2) + 0.0075 \times (14/62) \times \text{NO}_3) \quad (2)$$

Moreover, the induced/indirect¹ N_2O -N emission was estimated using a simple default value of 0.01 kg $\text{N}_2\text{O-N/kg NH}_3\text{-N}$ or $\text{NO}_x\text{-N}$.

Nitrate leaching to the ground water was also included in the LCI of ES cultivation. To achieve that, the SQCB- NO_3 model was employed and nitrate leaching was estimated as follows:

$$N = 21.37 + \frac{P}{c \times L} [0.0037 \times S + 0.0000601 \times N_{\text{org}} - 0.00362 \times U] \quad (3)$$

where “N” denotes the amount of $\text{NO}_3\text{-N}$ leaching (kg N/ha yr), “P” represents the total amount of water supplied by precipitation and irrigation (mm/yr), “c” is clay content (%), “L” is rooting depth (m), “S” represents nitrogen supply through fertilizers after subtraction of NH_3 , NO_x , and N_2O (kg N/ha), N_{org} is nitrogen in organic matter, and “U” stands for the amount of nitrogen taken-up by crops [52].

Since N requirement during ES cultivation was assumed to be supplied through urea application, fossil CO_2 emissions should also be taken into account. Accordingly, the IPCC 2006 guidelines were followed and the default value of 0.73 kg $\text{CO}_2\text{/kg urea}$ (a direct emission as a result of the application of urea fertilizer) was applied [54].

Heavy metal emissions into water were estimated based on a constant leaching rate as follows:

$$M_{\text{leach},i} = m_{\text{leach},i} \times A_i \quad (4)$$

where $m_{\text{leach},i}$ stands for a constant emission of heavy metals caused by agricultural inputs as well as deposition from the air. Accordingly, an allocation factor (A_i) was used to assess the share of agricultural inputs in the total inputs. Since conservation tillage was used and therefore, no erosion was considered for the ES farms, heavy metal emissions through erosion were ignored. Furthermore, the emissions to soil were calculated based on the balance between inputs into the soil (fertilizers, pesticides, seeds, and deposition) and outputs from the soil (exported biomass, leaching, and erosion).

Phosphorus leaching was estimated as a constant factor, i.e., 0.07 kg (P/ha*a). Moreover, Phosphate run-off to surface water was not considered in this study.

Table 1
Life cycle inventory of *Eruca Sativa* cultivation.

Flow	Unit	Value
A. Inputs		
1. Human labor	h	78.97
2. Machinery and equipment		
Tractor	kg	2.8
Combine ^a	kg	3
Fertilizer spreader	kg	117
Sprayer	kg	150
3. Diesel fuel	L	80
4. Chemical fertilizers		
Nitrogen (N)	kg	100
Phosphate (P_2O_5)	kg	85
Potassium (K_2O)	kg	35
Sulfur	kg	14
5. Chemicals	kg	3
6. Seed	kg	8
B. Output		
ES seeds and residuals	kg	4200
C. Transportation		
Seeds and residuals	tkm	420

^a Agricultural machinery for combined soil preparation and planting practices.

¹ Refers to volatilisation of N as NH_3 and oxides of N (NO_x), and the deposition of these gases and their products NH_4^+ and NO_3^- onto soils and the surface of lakes and other water bodies.

During *ES* cultivation, farm preparation, planting, application of fertilizers and pesticides were performed by means of agricultural machineries. Obviously, these farm operations were accompanied with the application of diesel fuel leading to vast amounts of direct emissions. The estimation of diesel fuel consumption during field operations and its corresponding emissions were carried out as described by Khoshnevisan et al. [55].

Apart from on-site emissions, LUC was also included in this study. As mentioned earlier, marginal and set-aside lands were considered for *ES* cultivation. It has been well documented that cultivation in these types of land could result in increased carbon pool in the soil [56–58]. As instructed by IPCC [59], two periods were considered for LUC effects, i.e., a payback time of 20 years in which the carbon pool would increase and after 20 years when a new equilibrium would be achieved [3]. An increase rate of 0.2–1.1 t C/ha yr change in soil organic carbon (SOC) due to the conversion of set-aside land to crop land has been reported in the literature [60,61]. In this study an average carbon sequestration rate of 0.6 t C/ha yr was considered. The capacity of the developed biorefineries were assumed to be 105 kt *ES* feedstock, meaning that 25 kha of land were needed to meet biorefineries' feedstock demands. Accordingly, 15 kt C/yr equals to 55 kt CO₂-eq/yr could be potentially stored in the soil pool. GHG effects induced by LUC can be summarized as follows:

$$\text{GHG}_{\text{LUC}} = \Delta\text{SOC} + \text{CH}_4 + \text{FM} + \text{N}_2\text{O} \quad (5)$$

where ΔSOC stands for change (either increase or decrease) in SOC, CH₄ refers to soil methane emissions in response to fertilizer use, FM is the GHG emissions during the production of the additional fertilizers used to maintain crop yields, and N₂O is the soil N₂O emission induced by the use of the additional N fertilizer [35].

2.2.2. *ES*-based biorefinery

ES seeds and residuals were harvested and transported to the biorefineries using 40-tonne trucks. In this context, the highest recommended limit of distance between farms and biorefineries, i.e., 100 km, was considered [3]. Processes were basically selected based on the composition of the raw material. *ES* contains about 13% oil which can be converted into biodiesel. The other main constituent of this plant is lignocellulosic materials. In addition to biodiesel, production of ethanol and biogas (*Sc-1* and *Sc-2*), or production of biomethane (*Sc-3*) are two possible scenarios for conversion of lignocelluloses to biofuels. In typical biodiesel plants, biodiesel is produced via reacting the plant oil with an alcohol mostly methanol. However, methanol is generally produced from fossil resource and therefore, in the present study, application of ethanol produced from the lignocellulosic fraction of the *ES* plant as renewable material was considered (*Sc-1*). Moreover, *Sc-1* was compared with a similar process in which methanol was used (*Sc-2*). *ES* oil was extracted by cold mechanical press and was stored in storage tanks at 80 °C for 24 h in order to remove extra moisture. The remaining lignocellulosic parts of the *ES*, i.e., crushed stem and leaves, as well as the seed cake were accumulated in piles and were used for the production of ethanol or biomethane. The biorefinery was developed with an annual capacity of 105 kMt (kilo metric tonne) *ES* plant containing 24% w/w free fatty acid. In this plant, an acid pretreatment step was used to reduce free fatty acid content to 1.9% w/w. The main reactions and processes used in the developed biorefineries, e.g., feed processing, transesterification, ethanol/methanol recovery, etc. were taken from laboratory experiments [19], and the inventory data were obtained by process simulation in Aspen Plus® simulation software [62].

Scenario 1. (*Sc-1*): Biodiesel production by transesterification of

oil with ethanol; and production of ethanol, heat, and power from lignocellulosic residuals.

The pretreated raw oil was sent to the transesterification unit where biodiesel and glycerol were produced by alkali transesterification reaction of the oil with ethanol. In this scenario, ethanol was a byproduct produced from the lignocellulosic residues. A part of this byproduct was sent back to the transesterification process for biodiesel production. Transesterification reaction was performed at 60 °C for 90 min. The final product consisted of two liquid phases which were separated by settling. The upper phase was rich in fatty acid ethyl esters (biodiesel) while the bottom phase was rich in glycerol. Both phases were contaminated with unreacted oil, ethanol, catalyst, and small amounts of soap produced during the transesterification step. Therefore, biodiesel underwent a purification step in order to meet the ASTM D6751 or EN 14214 quality standard for biodiesel (B₁₀₀). According to these standards, maximum impurities of biodiesel should not exceed 0.05% v/v. Thus, biodiesel was purified in a distillation tower with 24 sieve trays. The column was designed with 80% tray efficiency and operated at 10 kPa (absolute). The biodiesel product from the column overhead had a 99.96% v/v purity corresponding to 99% biodiesel recovery in the column. The unreacted oil was also recovered from the bottom of the distillation column containing 94% w/w oil. This oil was recycled back into the transesterification reactor. A column was also used for the purification of glycerol to 92% w/w concentration. The column had 4 sieve trays with 80% efficiency and was operated at a pressure of 40 kPa (absolute).

The lignocellulosic residues of the *ES* were pretreated with 8% w/v NaOH, at 100 °C for 60 min. Upon the completion of the pretreatment, the solid fraction was separated by filtration. The liquid filtrate contained hydrolyzed mono- and oligo-saccharides which were then used in the anaerobic digestion after neutralization. The solid fraction was washed in a multi-stage counter current solid wash to remove the remaining NaOH. Then, water and cellulolytic enzymes were added to the pretreated solid residues and the slurry was used for ethanol production in a simultaneous saccharification and fermentation (SSF) process. The beer stream leaving the fermenters, contained ethanol, xylose, lignin, unfermented hexoses, and fermentation byproducts. A three-column distillation unit, which consisted a stripper (beer column), a rectifier, and a scrubber column, was considered for ethanol purification. The stillage exiting from the bottom of the beer column, contained lignin and non-fermentable sugars produced during the hydrolysis process. Since lignin has a high heating value and is suitable for combustion, therefore, it was separated from the beer column stillage by filtration and was used for combustion. The filtrate from the lignin separation as well as the filtrate from the pretreatment process were sent into an anaerobic digester for biogas production. The effluent from the anaerobic digestion was treated in an aerobic digestion unit and was released as wastewater. Biogas, lignin, and sludge produced in the anaerobic and aerobic digestions were finally burnt in an incinerator for heat and power production. The whole process can be seen in Fig. 2 and the corresponding inventory data are shown in Table 2.

Scenario 2. (*Sc-2*): Biodiesel production by the transesterification of oil with methanol; and production of ethanol, heat, and power from the lignocellulosic residuals.

The processes in this scenario were similar to those of *Sc-1* except that instead of ethanol, methanol was used for biodiesel production in the transesterification unit. In contrast to ethanol, methanol was produced from fossil fuel resources. The excess methanol was separated in a distillation unit and was sent back to the transesterification reactor. The block diagram of this scenario

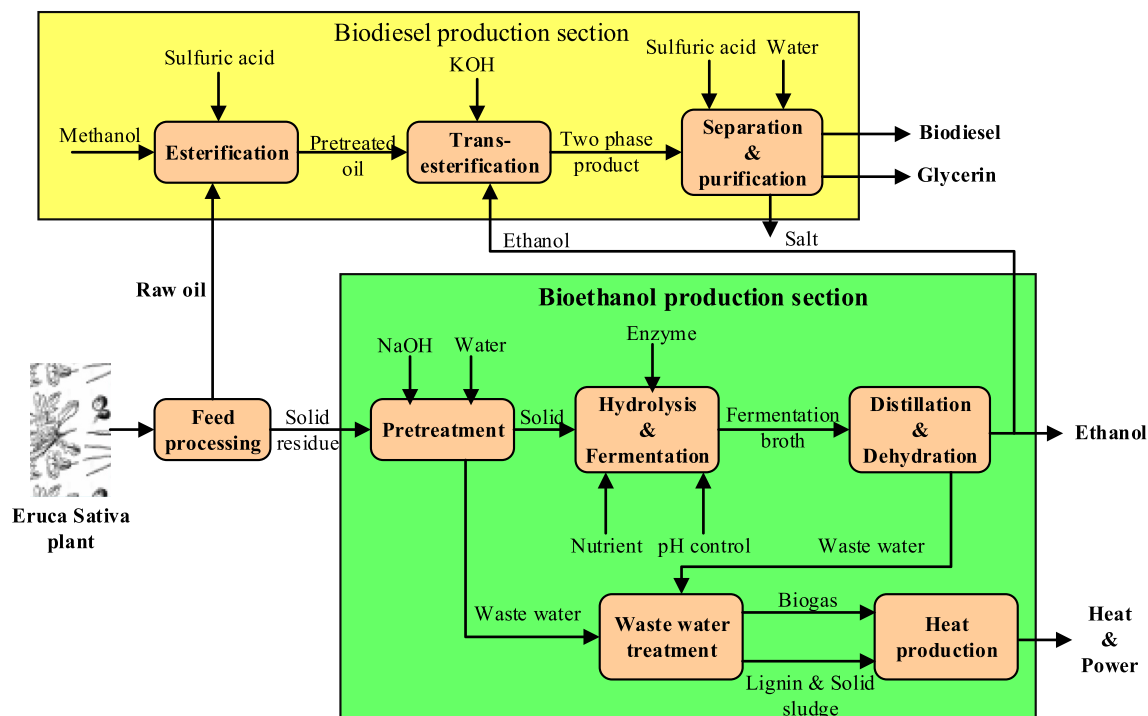


Fig. 2. Block flow diagram of the scenario 1 (Sc-1).

can be seen in Fig. 3 and the corresponding inventory data are shown in Table 2.

Scenario 3. (Sc-3): Biodiesel production by the transesterification of oil with methanol; and production of biomethane, heat, and power from the lignocellulosic residuals.

In this scenario, the units for feed handling, transesterification, biodiesel and glycerin purification, as well as pretreatment of lignocelluloses were similar to the Sc-2. However, the pretreated lignocellulosic residual of ES plant were sent to the anaerobic digestion unit. Afterwards, the produced biogas was upgraded and compressed to be used as vehicle fuel or to be injected into the gas grid. Among different technologies for biogas upgrading, water scrubbing with regeneration was chosen to minimize chemicals utilization and the associated costs [63]. Other combustible residues including lignin and sludge were sent to the combined heat and power (CHP) unit for heat and power generation. The block diagram of Sc-3 can be seen in Fig. 4 and the corresponding inventory data are shown in Table 2.

Although the amount of raw material used in the three scenarios was similar, there were a number of differences in the processes involved. The biodiesel production process includes esterification reaction and purification. Although the conversion rates of the plant oil in the reactors were different, the unreacted oil would be purified and recycled back to the esterification reaction. Thus, the theoretical amount of biodiesel produced was similar in all processes. Nevertheless, the small differences in biodiesel purities were ascribed to the existing differences in the purification efficiencies of the distillation units. Single pass conversion rate of the esterification reaction in Sc-1 was 85% while for the other two scenarios, it stood at 93%. Thus, the composition of the reaction products was not similar in the three scenarios and the details of the distillation unit in Sc-1 differed from Sc-2 and Sc-3. For instance, in Sc-1, the main reaction products were biodiesel, ethanol, ES oil, and glycerol while for Sc-2 and Sc-3, methanol was

present instead of ethanol and higher percentage of oil and less percentage of biodiesel was present. These differences led to higher amounts of biodiesel losses in the distillation unit of Sc-1 compared with Sc-2 and Sc-3.

2.2.3. Multi-functionality of biorefineries and allocation method

Since biorefineries simultaneously produce a number of marketable co-products, multi-functionality is a relevant problem which should be dealt with in LCA evaluations. A number of studies have been conducted to illustrate how the choice of allocation method could significantly affect the final results in environmental assessment of biofuel production systems [64,65]. Accordingly, in this study, system expansion with substitution was employed in which ES biodiesel was selected as the main product while the co-products (e.g., electricity, ethanol, heat, etc.) were given credits. Ethanol, produced in Sc-1 and Sc-2, was given credit because it was assumed that it could avoid gasoline consumption while the biomethane produced in Sc-3 was assumed to avoid natural gas consumption.

2.2.4. Biodiesel distribution and combustion

Generally, once biodiesel is produced, it needs to be distributed to filling stations. An average distance of 100 km was considered between biorefineries and filling stations as proposed previously [3]. For distribution of the diesel fuel, the average distance between the petroleum refineries and the filling stations was considered to be 300 km. Engine emissions including carbon dioxide, carbon monoxide, nitrogen oxides, hydrocarbons, and soot were estimated based on a literature review [38,39,66] and were compared for the combustion of B100 and diesel.

2.2.5. Life cycle impact assessment (LCIA)

The results of the LCI were keyed into SimaPro 8.3 and LCIA was carried out using IMPACT 2002 + method. This method was used because it is a combination of IMPACT 2002, Ecoindicator 99, CML,

Table 2
Life cycle inventory of different *Eruca Sativa* based biorefinery scenarios.

Items	Unit per year	Sc-1	Sc-2	Sc-3
Feed processing				
ES seeds	kt	50.69	50.686	50.686
ES residuals	kt	54.27	54.268	54.268
Electricity	kWh			
Belt Conveyer seeds		59,680	59,680	59,680
Belt Conveyer residuals		59,680	59,680	59,680
Cold filter press		148,000	148,000	148,000
Wood mill		1,040,000	1,040,000	1,040,000
Oil pump		1712	1712	1712
Esterification unit				
Methanol	kt	0.41	0.41	0.41
Sulfuric acid	kt	0.04	0.04	0.04
Steam	kt	2.99	2.99	2.99
Transesterification unit				
Ethanol (Recycled)	kt	3.07	×	×
Methanol	kt	×	1.084	1.084
Methanol (Recycled)		×	2.07	2.07
KOH	kt	0.11	0.11	0.11
Electricity	kWh			
Mixer		240,000	240,000	240,000
Oil pump		4984	5056	5056
Methoxide pump		30,704	352	352
Coil of reactor		1712	763,768	763,768
Ethanol/Methanol recovery Unit				
Electricity	kWh			
Pumps		7008	6624	6624
Cooler		1,183,048	925,568	925,568
Steam	kt	4.89	5.86	5.86
Biodiesel purification unit				
Steam	kt	10.47	5.79	5.79
Glycerol separation unit				
Sulfuric acid	kt	0.17	0.17	0.17
Electricity	kWh			
Sediment centrifuge		4000	4000	4000
Steam	kt	0.46	0.29	0.29
Pretreatment Unit				
NaOH	kt	43.07	43.07	47.72
NaOH (recovered)	kt	96.23	96.23	91.58
Steam	kt	114.01	114.01	848.67
Saccharification & fermentation unit				
Nutrient	kt			
Triple super phosphate		2.68	2.68	×
Urea		1.79	1.79	×
PH control material	kt			
Sodium carbonate		0.2	0.2	×
Enzyme	kt	7.69	7.69	×
Cell mass	kt	1.12	1.12	×
Electricity	kWh			
Coil of preheater fermenter		3,261,632	3,262,672	×
Steam	kt	0.13	0.13	×
Biogas production unit				
PH control material	kt			
Sodium carbonate		×	×	1.22
Steam	kt	×	×	100.78
Biogas upgrading unit				
Electricity	kWh			
Compressor		×	×	5,699,680
Ethanol purification unit				
Steam	kt	73.12	73.12	×
Solid separation unit				
Electricity	kWh			
Filter press		704,000	704,000	×
Waste water treatment unit				
Steam	kt	32.16	32.16	×
Electricity	kWh			
Electro dialysis		108,279	108,279	126,395.2
Pump after aerobic digestion		33,024	33,024	×
Aerators for aerobic digestion		1,237,512	1,237,512	61,055.2
Feed pump		×	×	5512
Recycle pump		×	×	12,920

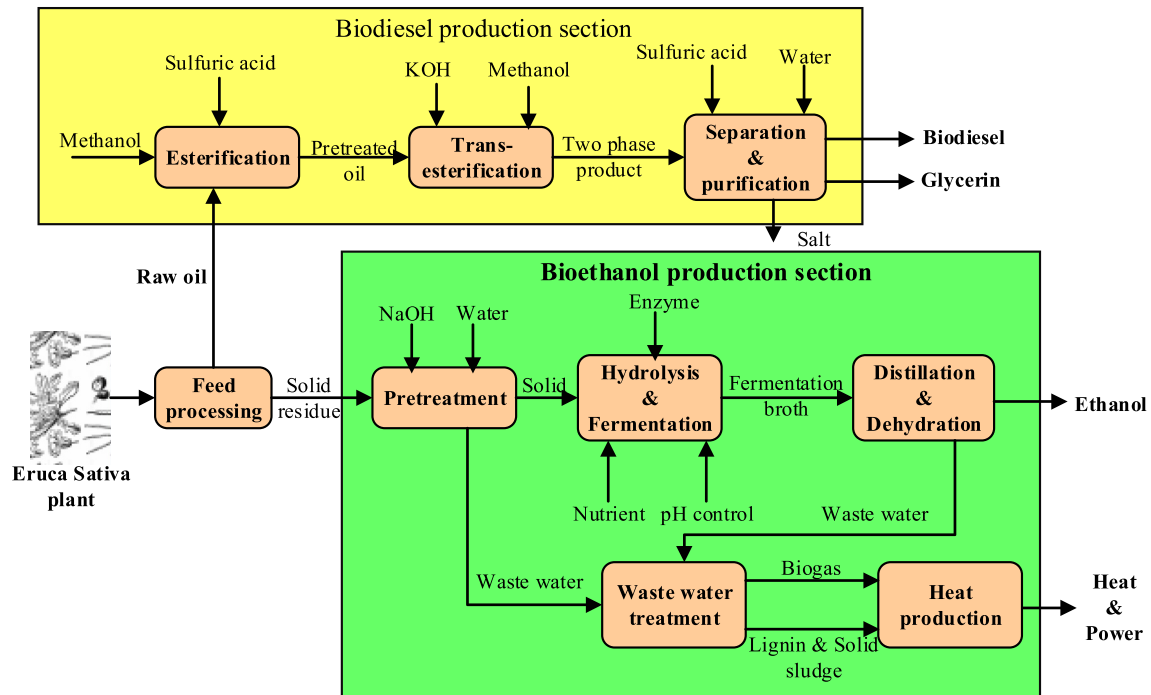


Fig. 3. Block flow diagram of the scenario 2 (Sc-2).

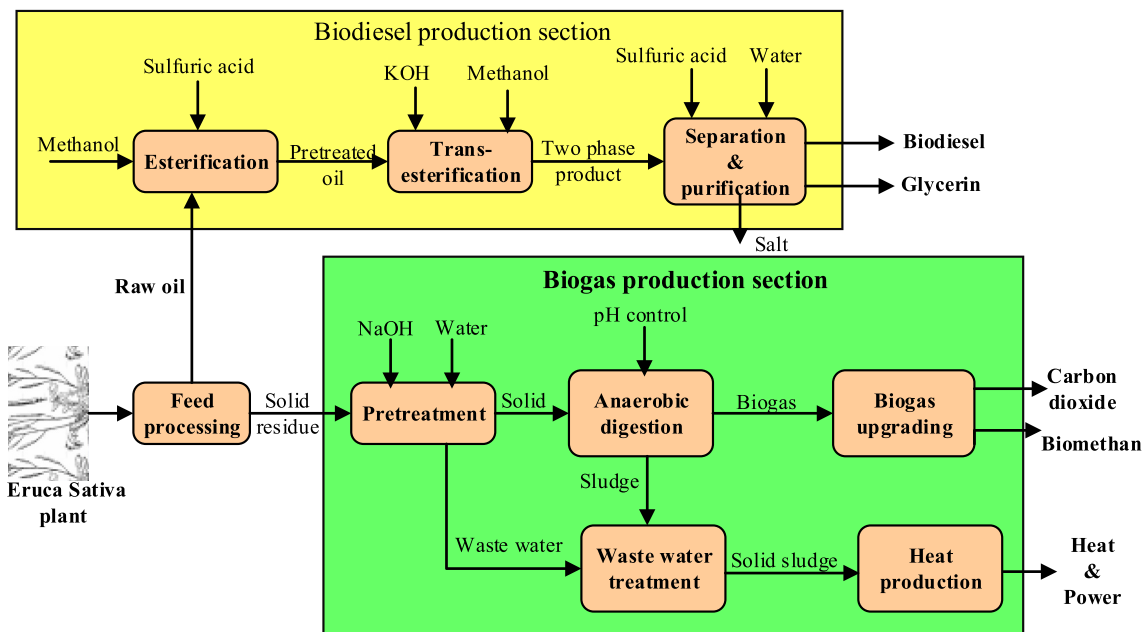


Fig. 4. Block flow diagram of the scenario 3 (Sc-3).

and IPCC methods. Such combination allows the execution of both problem-oriented and damage-oriented LCA for better interpretation of the results obtained [67]. The four damage categories involved in this method, i.e., Human health, Ecosystem quality, Climate change, and Resources, were assessed and three developed scenarios along with the reference system were compared using these damage categories.

Calculation of the energy indices can also be regarded as one of the most important steps in evaluating any renewable energy

systems because these indices could provide insights into the relationship between the amount of energy invested and the amount of energy produced. They also help to better understand if a system under evaluation is an “energy sink” or an “energy storage”. Net Energy Gain (NEG) and Fossil Energy Ratio (FER) are the most important and relevant energy indices used for assessment of energy balance in energy systems [34,46,68]. These energy indices were used to evaluate if the developed biorefineries were energy sink or not.

$$\text{NEG} = \text{Energy content of outputs (MJ)} - \text{Net energy inputs (MJ)} \quad (6)$$

$$\text{FER} = \text{Renewable Energy Output (MJ)} / \text{Fossil Energy Input (MJ)} \quad (7)$$

3. Results and discussions

This study was conducted to find out the most sustainable biorefinery procedure for *ES* as feedstock. More specifically, biodiesel production as well as a combination of different co-products, i.e., ethanol, biomethane, glycerin, heat, and power were taken into account. The outputs of the mentioned biorefineries are presented in Table 3. As can be observed, what distinguished Sc-1 and Sc-2 from Sc-3 was the production of bioethanol in the first two scenarios and the production of biomethane in the third one. It should be highlighted that in both Sc-1 and Sc-2, biogas was also produced but it was assumed to be directly burnt in a CHP due to its low purity and consequently heat and power were generated. In contrast to Sc-1 and Sc-2, the produced biomethane in Sc-3 had a higher purity which could meet home cooking fuel and transportation fuel standards. Therefore, it was assumed to be directly used as fuel for transportation or home cooking purposes. In another word, the biogas produced in Sc-1 and Sc-2 was only as much as 20% of the amount produced in Sc-3. Furthermore, the purity of biomethane generated in Sc-1 and Sc-2 was only 50% v/v while in the Sc-3 this value stood at 61%. Based on our preliminary investigations (data not shown), biogas upgrading was not economically feasible for the first two scenarios, and so it was burnt directly.

The gross electricity production in Sc-1, Sc-2, and Sc-3 were approximately 222, 222, and 179 TJ/yr, respectively. The values presented in Table 3 are the net electricity generation after subtracting the plant's electricity requirements. From the productivity point of view, Sc-2 was dominated by Sc-1 in terms of the total

amount of biodiesel produced but the amount of the produced bioethanol under Sc-2 conditions was 21% higher than that of Sc-1.

3.1. Greenhouse gas (GHG) balance

The results of the GHG balance and savings related to the combustion of B100 (both for the first 20 years and beyond) and neat diesel for the production of 1 GJ energy are tabulated in Table 4. A 100-year time horizon was considered for the characterization of global warming potential.

As shown in Table 4, only Sc-2 had a negative GHG balance during both periods with and without considering CO₂ sequestration. More specifically, the total GHG emissions of this scenario for the first 20 years was estimated at −384.05 kg CO_{2,eq}/GJ, out of which −317.37 kg CO_{2,eq}/GJ was caused by the LUC effect. Moreover, even after reaching a new equilibrium in soil carbon pool, the combustion of B100 led to lower GHG emissions compared with neat diesel combustion, i.e., 140 times lower than that of neat diesel.

As presented, the combustion stage of Sc-1 had no effects on the Climate change damage category owing to the fact that all CO₂ emissions released from *ES* biodiesel were considered as completely biogenic because the ethanol used for biodiesel production were assumed to be of biomass origin (ethanol was completely supplied internally by the biorefinery). In contrast, the combustion stage of Sc-2 and Sc-3 was responsible for 13.2 kg CO_{2,eq}/GJ because in these scenarios fossil-based methanol were used for biodiesel production, therefore 90% of the total CO₂ emission released from *ES* biodiesel combustion were assumed to be of biomass origin [54]. The remaining 10% was not considered biogenic since biodiesel conversion required use of methanol which is largely produced from natural gas.

Having considered the different stages of all scenarios, the cultivation stage was found to be the hotspot where out of the total GHG emissions released per GJ energy produced, 163–168 kg CO_{2,eq} was related to the *ES* production at farms. In another word, the evaluation of the Climate change damage category showed that the production of 1 t of *ES* feedstock including 515 kg straw and 485 kg seeds (on a wet basis) was responsible for emissions of 278 kg CO_{2,eq}. More specifically, on-site emissions contributed 69% of the total GHG emissions at farm level followed by the production of N- and K-based fertilizers with a share of 10 and 9%, respectively. These findings were in line with those reported by Rajaeifar et al. [34] who investigated the combustion of olive pomace oil biodiesel (B100) and argued that the agriculture stage made up the major proportion of the total GHG emissions (48–60%).

The N₂O emission caused by the application of N-based fertilizers and carbon dioxide emissions caused by both the application of urea and the combustion of diesel fuel during farm operations were the most important on-site emissions which played the most pivotal role at the cultivation stage. As mentioned earlier, little has

Table 3

The products of the developed biorefinery scenarios. The capacity of each plant was assumed to be approximately 105 kt/yr of feedstock including *Eruca Sativa* seeds and residuals.

Products	Unit	Sc-1	Sc-2	Sc-3
Biodiesel	kt	13.61	13.17	13.17
Bioethanol	kt	9.016	10.89	—
Electricity	TJ	191.54	191.86	146.12
Heat	TJ	454.58	454.56	365.36
Biomethane	kt	—	—	8.83
Glycerol	kt	1.12	1.12	1.12
Potassium sulfate	kt	0.16	0.16	0.16

Table 4

Total greenhouse gas (GHG) emissions and savings as a result of the combustion of B100 within the framework of different biorefinery scenarios for the first 20 years (with soil CO₂ sequestration) and after 20 years (without soil CO₂ sequestration).

Item	Unit	Combustion	Diesel Production	Biodiesel Production	ES Farm	Transportation	CO ₂ sequestration	Grand Total	Savings (%)
Sc-1 < 20	kg CO _{2,eq} /GJ	0	0	11.78	163	6.31	−307.16	−126.07	177.22
Sc-2 < 20	kg CO _{2,eq} /GJ	13.20	0	−254.75	168.41	6.46	−317.37	−384.05	335.23
Sc-3 < 20	kg CO _{2,eq} /GJ	13.20	0	395.41	168.41	6.46	−317.37	266.12	−63.00
Sc-1 > 20	kg CO _{2,eq} /GJ	0	0	11.78	163	6.31	0	181.09	−10.92
Sc-2 > 20	kg CO _{2,eq} /GJ	13.20	0	−254.75	168.41	6.46	0	−66.68	140.84
Sc-3 > 20	kg CO _{2,eq} /GJ	13.20	0	395.41	168.41	6.46	0	583.48	−257.39
Neat diesel	kg CO _{2,eq} /GJ	120.27	35.86	0	0	7.13	0	163.26	—

been done on the environmental assessment and GHG analysis of ES cultivation making comparisons difficult. Nevertheless, a vast number of research studies have been conducted on GHG balance analysis of other oil crops, such as 570 kg CO_{2,eq}/t rain-fed canola [69], 248–757 kg CO_{2,eq}/t soybean [70,71], and 781–1640 kg CO_{2,eq}/t sunflower [72,73]. Accordingly, it could be concluded that the total GHGs emitted at the ES farm stage were lower than those reported for the other oil seeds. In addition to that, applying organic fertilizers and better farm management could still further improve the situation as well.

Another significant difference which distinguished Sc-2 from Sc-1 and Sc-3 was the biorefinery stage where the production of ES biodiesel under the conditions of this scenario led to more favorable outcomes compared with the other scenarios. As presented in Table 4, the biorefinery stage of Sc-2 had a negative GHG balance and this scenario as the best approach led to an avoided emission of 254.75 kg CO_{2,eq}/GJ. In contrast to Sc-2, the worst scenario, i.e., Sc-3, had a positive GHG balance and the production of 1 GJ energy by burning B100 resulted in 395.41 kg CO_{2,eq}. A detailed analysis revealed that at the biorefinery stage of Sc-3, steam and sodium hydroxide production constituted more than 99% of the total impacts on the Climate change damage category. The highest steam requirement was observed in the pretreatment unit of Sc-3 whose energy requirement was about 89% higher than those of Sc-1 and Sc-2. This difference was due to the fact that the anaerobic digestion was performed under thermophilic conditions at 57 °C. Thus, heating of the digesters with an average retention time of 20 d was significantly more energy-consuming compared with ethanol fermentation which was operated at 37 °C for 48 h only. No significant distinction could be drawn between these scenarios in terms of sodium hydroxide consumption. However, this should remain at the core of the future studies to find out more environmentally-friendly substitution options for sodium hydroxide to achieve lower environmental burdens in the production phase. These findings were in line with those published by Amouri et al. [74] who took into account a biodiesel plant for castor-based biodiesel production and reported a total GHG emission of 997.43 kg CO_{2,eq}/t biodiesel produced. They also concluded that the steam used for oil-extraction and biodiesel production was the main contributor to the total emitted GHGs.

Finally, the three scenarios investigated were not significantly different in terms of avoided GHG emissions caused by avoided products, i.e., the products which were given credits due to avoiding the production of fossil-based products such as electricity and heat. The corresponding avoided emissions for Sc-1, Sc-2, and Sc-3 were estimated at 5386.66, 5638.67 and 4148.82 kg CO_{2,eq}/t of ES biodiesel, respectively.

Owing to the fact that the dynamics affecting soil carbon pools are very site-specific and highly dependent on former and current agronomic practices, climate, as well as soil characteristics a sensitivity analysis was conducted. The mentioned parameters were changed and the influence of SOC changes on GHG balance was determined and the results are shown in Fig. 5. Accordingly, under warm weather conditions and through multiple soil management practices, i.e., full tillage, the SOC decreased which consequently resulted in increased GHG emissions. Under the aforementioned conditions, 1614 kg CO_{2,eq}/GJ was released due to decreased SOC. In contrast, under dry conditions, no-tillage, and the highest incorporation of organic matters, the carbon pool increased and the maximum carbon sequestration was estimated at 1.7 t/ha.yr equal to 6.2 t CO_{2,eq}/ha.yr.

3.2. Resources damage category

This damage category refers to primary energy consumption in a

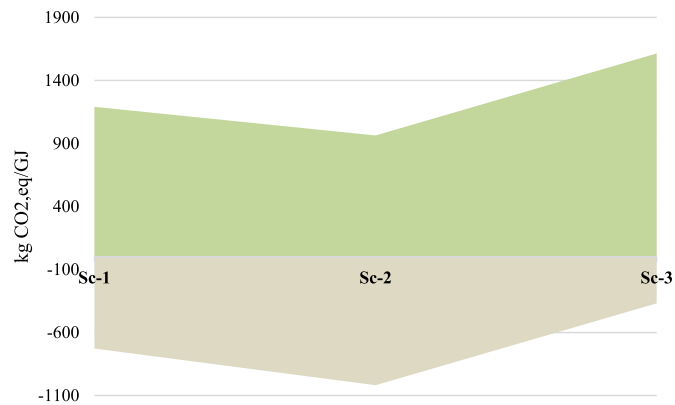


Fig. 5. Variation in GHG balance resulted from changes in soil organic carbon.

given activity or production process and encompasses two mid-points, i.e., “non-renewable energy consumption” and “mineral extraction” [67]. As tabulated in Table 5, in this damage category, the lowest impacts belonged to B100 under Sc-2 conditions while the highest impact was made by the B100 under Sc-3 circumstances. In another word, in comparison with neat diesel and under Sc-2 conditions, approximately a 200% reduction in primary energy consumption per 1 GJ energy produced was achieved. This significant achievement was obtained because in the biodiesel production stage (see Table 5), the avoided products led to a negative value in primary energy consumption, i.e., $-7.42\text{E}+03$ MJ primary/GJ. Moreover, by following the Sc-3 instructions, only 20.5% savings in this damage category could be obtained. As for the combustion of neat diesel, diesel production stage was the most important contributor to the Resources damage category and out of the total impact made, $5.41\text{E}+03$ MJ primary/GJ resulted from the diesel production alone.

In Sc-1 and Sc-2, the hotspot was found to be the ES cultivation stage. The urea used to meet plants' nutrient requirements and the diesel fuel required for farm operations caused such a significant impact on the Resources damage category. At the cultivation stage, the production of 1 t ES feedstock led to $3.08\text{E}+3$ MJ primary energy consumption, out of which 42% (i.e. $1.29\text{E}+3$ MJ primary) and 26% (i.e. 805 MJ primary) were respectively imposed by urea and diesel fuel production.

A detailed analysis indicated that in fact the biorefinery stage distinguished Sc-1 and Sc-2 from Sc-3 in the Resources damage category. More specifically, the biorefinery stage of Sc-1 and Sc-2 required significantly higher primary energy/GJ of $2.91\text{E}+03$ and $3.50\text{E}+03$ MJ, respectively. However, the avoided products at this stage in these scenarios compensated for such high primary energy requirements, resulting in an avoided primary energy requirement of $9.90\text{E}+03$ and $1.08\text{E}+04$ MJ/GJ for Sc-1 and Sc-2, respectively. In contrast, the co-products produced at the biorefinery stage of Sc-3 could only decrease $5.91\text{E}+03$ MJ primary energy/GJ and hence, Sc-3 could not compete with Sc-1 and Sc-2 in terms of Resources damage category.

These findings were comparable with those of the other studies whose main focus was on the biorefinery concept [3,18,34]. They also unanimously concluded that due to the significant amounts of non-renewable and primary energy carriers used in fossil-oriented systems, those systems were not capable of competing with biorefinery-based systems from the Resources damage category point of view [3,18,34]. Generally and according to the results of the present study, at the biorefinery scale, production and consumption of ES biodiesel under the circumstances of the three scenarios could help to reduce the consumption of primary energy compared

Table 5

Results of three damage category and the amount of savings achieved through the deployment of different biorefinery scenarios and comparison with neat diesel as fossil-based reference system.

Item	Unit	Combustion	Diesel Production	Biodiesel Production	ES Farm	Transportation	Grand Total	Savings (%)
Resources								
B100-Sc-1	MJ primary/GJ	0.00	0.00	-7.07E+03	1.81E+03	1.11E+02	-5.15E+03	193.47
B100-Sc-2	MJ primary/GJ	0.00	0.00	-7.42E+03	1.87E+03	1.14E+02	-5.44E+03	198.73
B100-Sc-3	MJ primary/GJ	0.00	0.00	2.40E+03	1.87E+03	1.14E+02	4.38E+03	20.51
Neat diesel	MJ primary/GJ	0.00	5.41E+03	0.00	0.00	1.03E+02	5.51E+03	–
Human Health								
B100-Sc-1	DALY/GJ	2.75E-04	0.00	2.75E-04	4.00E-04	4.98E-06	1.38E-03	-323.31
B100-Sc-2	DALY/GJ	2.75E-04	0.00	8.08E-05	4.13E-04	5.09E-06	7.74E-04	-137.42
B100-Sc-3	DALY/GJ	2.75E-04	0.00	9.42E-04	4.13E-04	5.09E-06	1.64E-03	-403.07
Neat diesel	DALY/GJ	2.58E-04	6.12E-05	0.00	0.00	6.57E-06	3.26E-04	–
Ecosystem quality								
B100-Sc-1	PDF/m ² .yr.GJ	1.60E+01	0.00	9.82E+00	1.78E+02	6.49E+00	2.10E+02	-201.72
B100-Sc-2	PDF/m ² .yr.GJ	1.60E+01	0.00	2.65E+02	1.84E+02	6.64E+00	4.71E+02	-576.72
B100-Sc-3	PDF/m ² .yr.GJ	1.60E+01	0.00	1.91E+01	1.84E+02	6.64E+00	2.25E+02	-223.28
Neat diesel	PDF/m ² .yr.GJ	1.41E+01	4.82E+01	0.00	0.00	7.34E+00	6.96E+01	–

with neat diesel.

3.3. Human health damage category

Human health damage category is the sum of the following midpoints: “human toxicity”, “respiratory effects”, “ionizing radiation”, “ozone layer depletion”, and “photochemical oxidation” [67]. The results of the Human health damage category are shown in Table 5. As presented, compared with the combustion of neat diesel, the combustion of B100 under the conditions of all scenarios resulted in a positive increase in this damage category. Sc-3 was found as the worst scenario with a value of 1.64E-03 DALY/GJ (Disability-Adjusted Life Years), followed by Sc-1 and Sc-2 with values of 1.38E-03 and 7.74E-04 DALY/GJ, respectively. In another word, Sc-3 led to over 400% higher impacts on this damage category when compared with neat diesel combustion. The production of 1 GJ energy through the combustion of B100 under Sc-2 conditions led to the lowest impact on this damage category in comparison with Sc-1 and Sc-3. In spite of that, the overall impact of Sc-2 on this damage category was approximately 137% more in comparison with neat diesel combustion.

What marked Sc-2 as pollutant compared with the combustion of neat diesel was the ES cultivation stage, followed by the biorefinery phase. In fact, the emissions of NH₃ and NO_x from N-based fertilizers, as well as PM_{2.5} due to the combustion of diesel in the agricultural machinery made the cultivation stage considerably polluting in terms of Human health damage category. At the biorefinery stage of Sc-2, such pollution was caused by the production of sodium hydroxide in the background system (66% of the total impact), followed by on-site emissions in the biorefinery plant (12% of the total impact) including nitrogen oxide and sulfur dioxide released due to sludge combustion. These results were similar to the those of Amouri et al. [74], who concluded that the cultivation stage and biodiesel production (including oil extraction) were respectively responsible for 50.15 and 49.5% of total impacts in the Human health impact potential. Furthermore, they impacts observed on Human health in the cultivation stage were ascribed to the farming operations and fertilizer usage. Similar results were also reported in different investigations conducted by Xue et al. [75] and Rajaeifar et al. [34].

3.4. Ecosystem quality damage category

The fourth damage category evaluated was the Ecosystem quality, expressed in PDF/m².yr (Potentially Disappeared Fraction of

species per m² per yr) [67]. This damage category consists of several midpoints, some of which are “aquatic ecotoxicity”, “terrestrial ecotoxicity”, “terrestrial acid/nutr”, “land occupation”, “aquatic acidification”, and “aquatic eutrophication” and is used to take into account the level of disruption in ecosystems [67]. The results obtained are illustrated in Table 5. As observed, no scenario could compete with the combustion of neat diesel in terms of Ecosystem quality damage category. According to these findings, the combustion of B100 in all three scenarios led to higher negative environmental impacts compared with the combustion of neat diesel. Moreover, Sc-2 was found as the worst scenario with a value of 4.71E+02 DALY/GJ, followed by Sc-3 and Sc-1 with values of 2.25E+02 and 2.10E+02 DALY/GJ, respectively. In Sc-2 as the worst scenario, the biorefinery stage was responsible for 56% of all impacts in the Ecosystem quality damage category. More specifically, at the biorefinery stage of Sc-2, these impacts were predominantly caused by sodium hydroxide production and other inputs while the emissions had minor effects on this damage category. Overall, the impact of the combustion of B100 under Sc-2 circumstances on the Ecosystem quality damage category was 576.72% higher compared with neat diesel combustion.

In two of the investigated scenarios, i.e. Sc-1 and Sc-3, the cultivation stage played a significant role in the Ecosystem quality damage category. Production of each tonne of ES feedstock was responsible for 303 PDF/m², out of which on-site emissions contributed more than 95% of the total impact. More specifically, heavy metals emissions resulted from the application of chemical fertilizers had the most important contribution to this damage category (2.02E2 PDF/m².yr for each tonne of ES feedstock processed). Ammonia emissions from N-based fertilizers and NO_x emission due to the combustion of diesel by the agricultural machineries and the application of N-based fertilizers were second and third contributors to the Ecosystem Quality, respectively. These findings were in line with those of Xue et al. [75], Rajaeifar et al. [34] and Nanaki and Koroneos [76] who also identified NH₃ emissions caused by agricultural practices and leaching of nutrients as the main contributing factors in this damage category. Amouri et al. [74] also argued that the cultivation stage accounted for 78.3% of the impacts on the Ecosystem quality impact category, predominantly due to the energy required by the tillage.

3.5. Evaluation of energy indices and water footprint

NEG and FER were chosen in the present study as two prevalent energy indices and the results were compared for the three

developed biorefineries. As tabulated in Table 6, in two scenarios, i.e., Sc-1 and Sc-2, positive NEG values were obtained, meaning that in these scenarios the amount of the produced energy was higher than what invested. Accordingly, the biorefinery approach executed under the Sc-1 circumstances had the highest NEG of $5.40\text{E}+03$ MJ/t ES feedstock, meaning that per each tonne of ES feedstock processed in this biorefinery, $5.40\text{E}+03$ MJ net energy was obtained.

Due to the fact that land is a limiting factor for cultivation of energy crops, this energy index was also calculated on a land basis and the results are presented in Table 6. It was revealed that the ES cultivation in 1 ha and processing under the conditions of Sc-1 and Sc-2 would result in a significant positive net energy. Moreover, the FER calculated also proved that the produced energy by Sc-1 and Sc-2 were respectively 68% and 52% higher than the amounts of energy invested, meaning that these biorefineries were not “energy sink”.

The three scenarios were also compared based on the water footprint index. The results, as shown in Table 6, proved that Sc-3 consumed the least amount of water among the investigated scenarios. Although this finding seems promising, but owing to the fact that Sc-3 was “energy sink”, therefore, this scenario could not be considered as the most environmentally-friendly alternative to neat diesel. The amount of water consumed in Sc-2 was about 1.5 as much as that of Sc-1. In the cultivation stage of these scenarios, the same amount of water was consumed but what made Sc-2 more water-demanding stemmed from its feedstock biorefining stage. More specifically, the sodium hydroxide used in the biorefining stage was the most important contributor to water footprint index as the production of 1 kg sodium hydroxide consumed about 0.005 m^3 .

3.6. Overall assessment and perspectives

Finding appropriate feedstock for biodiesel production as transportation fuel has long been at the core of a vast number of research studies and energy policy perspectives have been developed and offered on the basis of lab-scale analyses [29,34,74,77]. However, since lab-scale analyses may result in over/under estimations when sustainability issues are taken into account, this study attempted to develop several scenarios on a biorefinery scale and to assess the energy and environmental perspectives of those biorefineries. The results obtained proved that the life cycle energy should be given priority in such assessments because if the biorefineries become “energy sink” and have a negative NEG, they cannot compete with fossil reference systems and consequently cannot be used as a primary source of energy. Accordingly, Sc-3 could no longer be considered as a suitable approach for providing future transportation fuel because of its negative NEG ($-3.27\text{E}+08$ MJ) and its FER of <1 (i.e., 0.82). A literature review showed that significantly different FERs have been reported previously for various types of biodiesel, even for those produced from the same feedstock. Some of these values are as follows: 1.97 for soybean biodiesel in Iran [5], 0.75 for soybean biodiesel in the US [78], 3.2 for soybean biodiesel in the US [79], 5.37 for palm oil biodiesel in Brazil [80], 1.64 palm oil biodiesel in Ireland [81], 3.5

palm oil biodiesel in Indonesia [82], and 2.3 for jatropha biodiesel in Tanzania [46]. In a study conducted on a switchgrass-based biorefinery whose products were considered to be gasoline, electricity, heat, and phenol, the energy ratio was reported to be 3.6 [3]. Having compared the FER obtained in the present study and those reported previously, it was revealed that although the values obtained herein were in an acceptable range, attempts should still be made to increase the FER by employing better processing management options.

The energy usage in all scenarios can be further reduced by application of process heat integration techniques. These could include the application of pinch analysis and heat integration with Aspen Energy Analyzer software. Furthermore, optimization of the distillation columns and using more efficient columns, e.g., multi pressure columns which are thermally coupled, could also decrease the energy demands of all processes. Concerning the NEG index, all scenarios had almost similar energy inputs and outputs except Sc-3 in which significant amounts of energy was consumed by biogas upgrading compressor. High energy consumption for biogas upgrading has always been an important issue when biomethane production is considered. Water scrubbing technology (used herein), the most popular method in the Europe, is performed at high pressures. This is due to the fact that the solubility of carbon dioxide in water is very low. Application of other methods such as pressure swing adsorption (PSA) or cryogenic method also requires high gas pressure and thus leading to high energy demands for compression. Application of chemicals such as amines increases the cost of chemicals and thus operating costs. When amines are used, although these solvents are recycled back to the process, the recovery of the solvent is not 100% and therefore, a make-up stream for the solvent is required. The most recent method currently emerging in the Europe is the application of membrane technology. This method also requires a compressor, but the amount gas which should be compressed is less than in the water scrubbing method. This is due to the fact that in the water scrubbing method, the compressor should pressurize a recycle gas stream in addition to the raw biogas while in the membrane technology, only the raw biogas should be compressed. Thus, it is predicted that membrane technology requires less energy compared with water scrubbing method. However, the economic feasibility of this type of process should still be further investigated.

Moreover, the energy indices illustrated that only Sc-1 and Sc-2 were acceptable in terms of energy payback. From the GHG balance point of view, Sc-2 proved to be a huge success because the combustion of B100 under the conditions of this scenario led to a 140% reduction in GHG emissions without even considering the improving effects of LUC. This scenario was also found considerably effective in saving primary energy. Taking Resources damage category into consideration showed that the use of ES biodiesel under the Sc-2 circumstances in comparison with neat diesel resulted in a significant decrease of approximately 200% per each GJ energy produced. It should be noted that although Sc-2 had a positive effect on energy and GHG balance, it had additional environmental impacts on other damage categories such as Human health and Ecosystem quality which could not be ignored. These findings were in line with those reported by Uihlein and Schebek [36] who considered a lignocellulose feedstock biorefinery whose outputs were ethanol, xylite, and lignin. They concluded that the performance of the biorefinery in some impact categories was worse compared with the fossil counterparts, while some advantages could be seen in other categories. Therefore, all the above-mentioned environmental hotspots should be taken into consideration within a complete framework and best decisions should be drawn according to the order of the different damages categories on a given priority list. Nevertheless and regardless of the power

Table 6
Evaluation of energy and water indices of the different biorefinery scenarios.

Energy indices	Unit	Sc-1	Sc-2	Sc-3
Total Net Energy Gain	MJ	$5.67\text{E}+08$	$4.94\text{E}+08$	$-3.27\text{E}+08$
Net Energy Gain	MJ/t feedstock	$5.40\text{E}+03$	$4.71\text{E}+03$	$-3.12\text{E}+03$
Net Energy Gain	MJ/ha	$2.27\text{E}+04$	$1.98\text{E}+04$	$-1.31\text{E}+04$
Fossil Energy Ratio	–	1.68	1.52	0.82
Water foot print	m^3/GJ	1.4	2.37	0.51

points and weak points of different scenarios, more sustainable processing management options should be constantly explored and evaluated.

From the economic point of view, biogas upgrading was the major hurdles. Based on a general engineering rule, i.e., “six-tenths-rule”, plants with higher capacities require less investment and operating costs per unit of product [83]. The annual costs for biogas upgrading may vary from 1.2 to 2.5 € cent/kWh of biomethane depending on the capacity of the plant. The smaller value corresponds to capacities of 1500–2000 Nm³/h raw biogas while the higher value corresponds to capacities of around 250 Nm³/h raw biogas [84]. The amount of raw biogas which was produced in Sc-1 and Sc-2 were about 520 Nm³/h which resulted in higher upgrading costs compared with Sc-3 which had a capacity of 2500 Nm³/h. Furthermore, the raw biogas in Sc-1 and Sc-2 contained 51% methane while in Sc-3, the methane content was 61%. Hence, based on this preliminary economic evaluation indicated that the cost required for manufacturing a biogas upgrading unit in Sc-1 and Sc-2 is not economically justified.

4. Conclusions and future outlook

Based on the results obtained herein, it could be concluded that the type of feedstock processing option could significantly affect the final results in terms of the environmental and energy indices. Accordingly, it was shown that under the conditions of Sc-2, the total GHG emissions was estimated at –67 kg CO_{2,eq}/GJ, even without considering the positive impact of LUC. Moreover, taking the LUC effect into account resulted in approximately 335% GHG savings compared with the combustion of neat diesel (–384.05 kg CO_{2,eq}/GJ vs. 163.26 kg CO_{2,eq}/GJ). The results obtained also revealed that only one approach (i.e., Sc-2) out of the three biorefinery scenarios could effectively reduce GHG emissions and compensate for the depletion of fossil resources compared with the fossil reference system investigated. In terms of GHG balance, ES cultivation was found to be the hotspot where out of the total GHG emissions released per GJ energy produced, 163–168 kg CO_{2,eq} was related to the ES production in farms.

From the energy balance point of view, two scenarios out of the three proved to be energy efficient. The calculated FER proved that the produced energy by Sc-1 and Sc-2 were respectively 68% and 52% higher than the amounts of the energy invested, resulting in positive NEG values. The outcomes of the present study showed that although biorefineries offer unique features as the most effective alternatives for mitigating climate change and reducing dependence on fossil fuels, the selection of biomass processing options and management decisions can considerably affect the final results in terms of environmental and energy balances. Moreover, if biorefineries are focused on transportation fuel production, a great deal of effort should still be made to have better environmental performance in Human health and Ecosystem quality damage categories. Using multi pressure columns which are thermally coupled could help achieving reduced energy demands and consequently decreased environmental intensity in biorefineries. Water scrubbing technology for biogas upgrading should also be replaced with membrane technology due to its less energy requirements. This study highly recommends that future studies shift their main focus towards biomass processing options and process optimization instead of feedstock alternatives to guarantee the future of the most sustainable biofuels.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.renene.2017.10.035>.

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